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1 UTCI - Why another thermal index?

2
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19 **Abstract**

20 The existing assessment procedures of the thermal environment in the fields of public weather
21 services, public health systems, precautionary planning, urban design, tourism & recreation
22 and climate impact research show significant shortcomings. This is most evident for simple
23 (mostly two-parameter) indices, when comparing them to complete heat budget models
24 developed since the 1960s. ISB Commission 6 took up the idea to develop a Universal
25 Thermal Climate Index (UTCI) which was to be based on the most advanced multi-node
26 model of thermoregulation representing the progress in science within the last 3 to 4 decades,
27 both in thermo-physiological and heat exchange theory.

28
29 Creating the essential research synergies for the development of UTCI required pooling the
30 multidisciplinary experts in the fields of thermal physiology, mathematical modelling,
31 occupational medicine, meteorological data handling (in particular radiation modelling) and
32 application development in a network. It was possible to extend the expertise of ISB
33 Commission 6 substantially by COST (A European programme of promoting Cooperation in
34 Science and Technology) Action 730 so that ultimately, for ISB and COST together, over 45
35 scientists from 23 countries (Australia, Canada, Europe, Israel, New Zealand, and the USA

1 worked together. The work was done under the umbrella of WMO- Commission on
2 Climatology CCI.

3

4 After extensive evaluations Fiala's multi-node human Physiology and thermal Comfort model
5 (FPC) was adopted for this study. The model was extensively validated applying as yet
6 unused data from other research groups, and extended for purposes of the project. This model
7 was coupled with a state-of-the-art clothing model considering the behavioural adaptation of
8 clothing insulation by the general urban population to actual environmental temperature.
9 UTCI was then derived conceptually as an Equivalent Temperature (ET). Thus, for any
10 combination of air temperature, wind, radiation, and humidity (stress), UTCI is defined as the
11 air temperature of the reference condition which would elicit the same dynamic response
12 (strain) of the physiological model as the actual conditions. As UTCI is based on
13 contemporary science its use will standardize applications in the major fields of human
14 biometeorology thus making research results comparable and physiologically relevant.

15

16 *Keywords: Outdoor climate, Thermal assessment, Index, Thermal stress, Thermo-physiology,*
17 *Model*

18

19 **Introduction**

20 The close relationship of humans to the thermal component of the atmospheric environment is
21 self-evident and belongs to everybody's daily experience. Thus, issues related to thermal
22 comfort, discomfort, and health impacts are the reason that the assessment and forecast of the
23 thermal environment is one of the fundamental and enduring themes within human
24 biometeorology. In this context the term "thermal environment" encompasses both the
25 atmospheric heat exchanges with the body (stress) and the body's physiological response
26 (strain).

27

28 The following fields of applications are considered as particularly significant for users:

29 1) Public weather service (PWS). The issue is how to inform and advice the public on
30 thermal conditions at a short time scale (weather forecast) for outdoor activities,
31 appropriate behaviour, and climate-therapy. Currently various national meteorological
32 services around the world are using a plethora of indices in their public weather

1 advice. But in an increasingly internationalized weather information sphere, the use of
2 local weather dialects seems no longer to be appropriate.

3 2) Public health system (PHS). In order to mitigate adverse health effects by extreme
4 weather events (here heat waves and cold spells) it is necessary to implement
5 appropriate disaster preparedness plans. This requires warnings about extreme thermal
6 stress so that interventions can be released in order to save lives and reduce health
7 impacts.

8 3) Precautionary planning. This refers to a wide range of applications in public and
9 individual precautionary planning such as urban and regional planning, and in the
10 tourism industry. The increasing reliability of monthly or seasonal forecasts should be
11 considered to help develop appropriate operational products.

12 4) Climate impact research in the health sector. The increasing awareness of climate
13 change and therewith related health impacts requires epidemiological studies based on
14 cause-effect related approaches.

15
16 Balancing the human heat budget, i.e. equilibration of the organism to variable environmental
17 (atmospheric) and metabolic heat loads is controlled by a very efficient (for healthy people)
18 autonomous thermoregulatory system. This is additionally supported by behavioural
19 adaptation (e.g. eating and drinking, activity and resting, clothing, exposure, housing,
20 migration) which is driven by conscious sensations of thermal discomfort. These capabilities
21 enable the (healthy) human being to live and to work in virtually any climate zone on earth,
22 albeit with varying degrees of discomfort.

23
24 The heat exchange between the human body and its environment takes place by sensible and
25 latent heat fluxes, radiation and (generally negligible) conduction. Comprehensively
26 characterising the thermal environment in thermo-physiologically significant terms requires
27 application of a complete heat budget model that takes all mechanisms of heat exchange into
28 account (Büttner, 1938; Parsons, 2003). Atmospheric environmental parameters governing all
29 of the abovementioned heat exchanges include air temperature, water vapour pressure, wind
30 velocity, mean radiant temperature including the short- and long-wave radiation fluxes of the
31 atmosphere (see Weihs et al., 2011 elsewhere in this issue), in addition to metabolic rate and
32 clothing insulation worn by the subject. Only thermal climate indices that incorporate all of
33 the parameters of the human heat budget can be universally utilised across the full gamut of

1 biometeorological applications, across all climate zones, regions and seasons (e.g. Jendritzky
2 and de Dear, 2009).

3

4 In recognition that the human thermal environment cannot be represented adequately with just
5 a single parameter, air temperature (T_a), over the last 150 years or so more than 100 simple
6 thermal indices have been developed, most of them two-parameter indices. For warm
7 conditions such indices usually consist of combinations of T_a and one of a variety of
8 expressions for humidity, while for cold conditions the combination typically consists of T_a
9 combined in some way with air speed (v). Simple indices are easy to calculate and therefore
10 easy to forecast. In addition they are readily communicated to the general public and
11 stakeholders such as health service providers (Koppe et al., 2004). However, due to their
12 simple formulation, i.e. neglecting significant fluxes or variables, these indices can never
13 fulfil the essential requirement that for each index value there must always be a corresponding
14 and unique thermo-physiological state (strain), regardless of the combination of the
15 meteorological input values (stress). Simple indices can only be of limited value, results are
16 often not comparable and often lead to misrepresentations of the thermal environment, and
17 additional features such as safety thresholds have to be defined arbitrarily and cannot be
18 transferred to other locations.

19

20 These inadequacies of two-parameter indices have prompted hundreds of attempts at
21 improvement The Wind-Chill Temperature (ISO 11079, 2007) and subsequently the New
22 Wind Chill Index (Osczevski and Bluestein, 2005) are illustrative in this regard; the turbulent
23 heat flux is disproportionate and has been critiqued by Shitzer (2006) and Shitzer and de Dear
24 (2006). In occupational health the Wet Bulb Globe Temperature (WBGT, ISO 7243, 1989)
25 evolved in the 1950s, but is still popular for considerations of humidity and thermal radiation
26 in warm environments. Comprehensive reviews of simple indices can be found in e.g., Fanger
27 (1970), Landsberg (1972), Driscoll (1992), and Parsons (2003).

28

29 During the last 40 years thermal biomereorology advanced significantly with the development
30 of heat budget models (see Stollwijk, 1971 and related 2-node model associated with Gagge
31 et al, 1986). Subsequent developments, still relatively simple, include models such as MEMI
32 with the output of PET (Höppe, 1984, 1999; Matzarakis et al., 2007), and the Outdoor

1 Apparent Temperature¹ (Steadman 1984, 1994). More comprehensive models and indices
2 based upon the human heat balance equation include the Standard Effective Temperature
3 (SET*) index (Gagge et al. 1986), and OUT_SET* (Pickup and De Dear 2000; De Dear and
4 Pickup 2000), which translates Gagge's indoor version of the index to an outdoor setting by
5 simplifying the complex outdoor radiative environment down to a mean radiant temperature
6 (T_{mrt}). Blazejczyk (1994) presented the man-environment heat exchange model MENEX,
7 while the extensive work by Horikoshi et al. (1995, 1997) resulted in a Thermal
8 Environmental Index. While the aforementioned heat budget models are applicable across the
9 full range of heat exchange conditions, the Predicted Heat Strain (PHS, ISO 7933, 2004)
10 which is used in occupational medicine, is relevant only to warm environments.

11
12 Fanger's (1970) PMV (Predicted Mean Vote) equation can also be included among the
13 advanced heat budget models if the improvement by Gagge et al. (1986) in the description of
14 latent heat fluxes by the introduction of PMV* is applied. This approach is generally the basis
15 for the operational thermal assessment procedure Klima-Michel-Model KMM (Jendritzky et
16 al. 1979, 1981; Jendritzky, 1990) of the German national weather service DWD (Deutscher
17 Wetterdienst) with the output parameter "Perceived Temperature (PT)" (Staiger et al. 1997;
18 VDI 2008) that considers behavioural adaptation by varying clothing. For more than two
19 decades KMM was the sole assessment procedure which has included a complete radiation
20 model to calculate T_{mrt} on basis of meteorological data. To date the German weather service
21 (DWD) is the only national weather service to run a complete heat budget model (KMM-PT)
22 on a routine basis specifically for applications in human biometeorology.

23
24 Although each of the heat budget models referred to above is, in principle, appropriate for use
25 in any kind of assessment of the thermal environment, none of them is accepted as a
26 fundamental standard, neither by researchers nor by end-users. This is probably because of
27 persistent shortcomings in relation to thermo-physiology and heat exchange theory. On the
28 other hand, it is surprising that after 40 years experience with heat budget modelling and easy
29 access both to computational power and meteorological data, the crude and basic empirical
30 indices like WBGT actually are still widely used. For comparisons of both selected simple
31 indices and also of more complex heat budget based approaches to the creation of a Universal

¹ The Indoor AT, which forms the basis of the US Heat Index, often used in outdoor applications by neglecting the prefix "Indoor" belongs to the simple two-parameter indices.

1 Thermal Climate Index (UTCI) see Blazejczyk et al. (2011) and Kampmann and Bröde (2009
2 and 2011 elsewhere in this issue).

3
4 A decade ago the International Society on Biometeorology ISB recognised these
5 shortcomings in thermal indices and established the Commission 6 "On the development of a
6 Universal Thermal Climate Index UTCI" (Jendritzky et al., 2002). Since 2005 these efforts
7 have been reinforced by the COST Action 730 (Cooperation in Science and Technology,
8 supported by the EU RTD Framework Programme) that provided ultimately the basis for
9 scientists from 23 countries (18 from Europe plus experts from Australia, Canada, Israel, New
10 Zealand, and the USA) to collaborate on development of such an index (COST UTCI, 2004).
11 The aim was an international standard based on the latest scientific progress in human
12 response related thermo-physiological modelling of the last four decades. The term
13 "universal" must be understood in terms of being appropriate for all assessments of outdoor
14 thermal conditions in major human biometeorological applications such as daily forecasts and
15 warnings of extreme weather, bioclimatic mapping, urban and regional planning,
16 environmental epidemiology and climate impacts research. This covers the fields of public
17 weather service, the public health system, precautionary planning, and climate impact
18 research in the health sector.

19

20 The Universal Thermal Climate Index UTCI must meet the following requirements:

- 21 1) Thermo-physiologically responsive to all modes of heat exchange between body
22 and environment.
- 23 2) Applicable for whole-body calculations but also for local skin cooling (frostbite)
24 (see Shitzer and Tikusis (2011) elsewhere in this issue)
- 25 3) Valid in all climates, seasons, and time and spatial scales
- 26 4) Appropriate for key applications in human biometeorology (listed above)

27

28

29 **Approach and results**

30

31 **Thermoregulation**

32

33 For the human being it is crucial to keep the body's core temperature within a narrow range
34 around 37°C, in order to ensure functioning of the inner organs and of the brain. In contrast
35 the temperature of the shell, i.e. skin and extremities, can vary significantly depending on the

1 volume of blood it contains, which in turn depends on metabolic and environmental heat
2 loads. Heat is produced by metabolism as a result of activity, sometimes increased by
3 shivering or slightly offset by mechanical work where applicable, e.g. when climbing. The
4 heat must be released to the environment by convection (sensible heat flux), conduction
5 (contact with solids), evaporation (latent heat flux), radiation (long- and short-wave), and
6 respiration (latent and sensible).

7

8 From the analytical point of view, the human thermoregulatory system can be separated into
9 two interacting sub-systems: (1) the controlling active system which includes the
10 thermoregulatory responses of shivering [thermo genesis] sweat moisture excretion, and
11 peripheral blood flow regulation (Fig. 1a), and (2) the controlled, passive system dealing with
12 the physical human body and the heat transfer occurring within it and at its surface (Fig. 1b).
13 This accounts for local heat losses from body parts by free and forced convection, long-wave
14 radiation exchange with surrounding surfaces, solar irradiation, and evaporation of moisture
15 from the skin and heat and mass transfer through non-uniform clothing. Under comfort
16 conditions the active system shows the lowest activity level indicating no strain. Increasing
17 discomfort is associated with increasing strain and related impacts on the cardiovascular and
18 respiratory system. The tolerance to thermal extremes depends on personal characteristics
19 (Havenith 2001, 2005): age, fitness, gender, acclimatization, morphology, and fat thickness
20 being among the most significant. Of these, age and fitness are the most important predictors
21 and both are closely correlated. High age and/or low fitness level are associated with low
22 cardiovascular reserve which causes low thermal tolerance.

23

24 Figure 1 a,b Schematic representation of human physiological and behavioural
25 thermoregulation (after Havenith 2001, Fiala et al. 2001)

26

27

28 **The heat budget**

29

30 The heat exchange between the human body and the thermal environment (Fig. 2) can be
31 described in the form of the energy balance equation (Eq. 1); essentially the first theorem of
32 thermodynamics applied to the body's heat sources (metabolism and environmental), and the
33 various avenues of heat loss to environment (Büttner 1938):

34

1 $M - W - [Q_H(T_a, v) + Q^*(T_{mrt})] - [Q_L(e, v) + Q_{SW}(e, v)] - Q_{Re}(T_a, e) \pm S = 0$ Eq. 1

2 M Metabolic rate (activity)

3 W Mechanical power

4 S Storage (change in heat content of the body)

5 **Peripheral (skin) heat exchanges:**

6 Q_H Turbulent flux of sensible heat

7 Q^* Radiation budget

8 Q_L Turbulent flux of latent heat (passive diffusion water vapour through the skin)

9 Q_{SW} Turbulent flux of latent heat (sweat evaporation)

10 **Respiratory heat exchanges:**

11 Q_{Re} Respiratory heat flux (sensible and latent)

12 **Thermal environmental parameters:**

13 T_a Air temperature

14 T_{mrt} Mean temperature

15 v Air speed relative to the body

16 e Partial vapour pressure

17

18 The meteorological input variables include air temperature T_a , water vapour pressure e , wind
 19 velocity v , mean radiant temperature T_{mrt} including short- and long-wave radiation fluxes, in
 20 addition to metabolic rate and clothing insulation. In eq. 1 the appropriate meteorological
 21 variables are attached to the relevant fluxes. However, the internal (physiological) variables
 22 (Fig. 1), such as the temperature of the core and the skin, sweat rate, and skin wettedness
 23 interacting with the environmental heat exchange conditions are not explicitly mentioned
 24 here.

25

26 Figure 2 The human heat budget (Havenith 2001)

27

28

29 Mathematical modeling of the human thermal system goes back 70 years. In the past four
 30 decades more detailed, multi-node models of human thermoregulation have been developed,
 31 e.g. Stolwijk (1971), Konz et al. (1977), Wissler (1985), Fiala et al. (1999, 2001), Huizenga et
 32 al. (2001) and Tanabe et al. (2002). These models simulate phenomena of human heat
 33 transfers within the body and at its surface, taking into account the anatomical, thermal and
 34 physiological properties of the human body (see Fig 1). Environmental heat losses from body

1 parts are modeled considering the inhomogeneous distribution of temperature and
2 thermoregulatory responses over the body surface. Besides overall thermo-physiological
3 variables, multi-segmental models are capable of predicting 'local' characteristics such as skin
4 temperatures of individual body parts. Validation studies have shown that recent multi-node
5 models accurately reproduce the human dynamic thermal responses over a wide range of
6 thermal circumstances (Fiala et al. 2001, 2003; Havenith 2001, Huizenga et al. 2001). These
7 models have become valuable research tools contributing to a deeper understanding of the
8 principles of human thermoregulation.

9

10 **Modelling**

11

12 As the assessment of thermal stress should ultimately be based on the physiological response
13 of the human body (thermal strain), ISB Commission 6 decided from the outset that this was
14 to be simulated by one of the most advanced (multi-node) thermo-physiological models. After
15 accessible models of human thermoregulation had been evaluated (Fiala et al. 1999; Tanabe et
16 al. 2002), the Fiala's multi-node human Physiology and thermal Comfort (FPC) model (Fiala
17 et al., 1999; 2001; 2003; 2010) was adopted for this study, extensively validated (Psikuta,
18 2009; Psikuta et al., 2007; see also Psikuta et al. 2011 elsewhere in this issue), and extended
19 for purposes of the project (Fiala et al., 2007; see also Fiala et al. 2011 elsewhere in this
20 issue).

21

22 The passive system of the Fiala model (Fiala et al. 1999, 2001) consists of a multi-segmental,
23 multi-layered representation of the human body with spatial subdivisions. Each tissue node is
24 assigned appropriate thermo-physical and thermo-physiological properties. The overall data
25 replicates an average person with respect to body weight, body fat content, and Dubois
26 surface area. The physiological data aggregates to a basal [whole body] heat output and basal
27 cardiac output, which are appropriate for a nude, reclining adult in a thermo-neutral
28 environment of 30°C. In these conditions, where thermoregulatory activity is minimal, the
29 model predicts a basal skin wettedness of 6%; a mean skin temperature of 34.4°C; and body
30 core temperatures of 37.0°C in the head core (hypothalamus) and 36.9°C in the abdomen core
31 (rectum) (Fiala et al. 1999). Verification and validation work using independent experiments
32 from air exposures to cold stress, cold, moderate, warm and hot stress conditions, and a wide
33 range of exercise intensities revealed good agreement with measured data for regulatory
34 responses, mean and local skin temperatures, and internal temperatures across the whole

1 spectrum of boundary conditions considered (Richards and Havenith 2007). By including as
2 yet unused data from other research groups the Fiala human Physiology and thermal Comfort
3 (FPC) model (Fiala et al. 2010) could be substantially advanced. FPC was adopted by the ISB
4 Commission 6 as the benchmark (“most advanced”) in terms of thermo-physiology and heat
5 exchange theory.

6
7 In the next step a state-of-the-art adaptive clothing model was developed and integrated
8 (Richards and Havenith, 2007; Havenith et al. 2011 elsewhere in this issue). This model
9 considers

- 10 1) the behavioural adaptation of clothing insulation observed for the general urban
11 population in relation to the actual environmental temperature,
- 12 2) the distribution of the clothing over different body parts providing local insulation
13 values for the different anatomical segments, and
- 14 3) the reduction of thermal and evaporative clothing resistances caused by wind and
15 limb movements of the wearer, who was assumed to be walking at a speed of 4
16 km/h on level ground (2.3 MET = 135 W/m²).

17
18 UTCI was then developed following the concept of an equivalent temperature. This involved
19 the definition of a reference environment with 50% relative humidity (but vapour pressure not
20 exceeding 20 hPa), with calm air and radiant temperature equalling air temperature, to which
21 all other climatic conditions are compared. Equal physiological conditions are based on the
22 equivalence of the dynamic physiological response predicted by the model for the actual and
23 the reference environment. As this dynamic response is multidimensional (body core
24 temperature, sweat rate, and skin wettedness etc. at different exposure times), a strain index
25 was calculated by principal component analysis as single dimensional representation of the
26 model response (Bröde et al., 2009a; 2009b). The UTCI equivalent temperature for a given
27 combination of wind, radiation, humidity and air temperature is then defined as the air
28 temperature of the reference environment that produces the same strain index value. As
29 calculating the UTCI equivalent temperatures by repeatedly running the thermoregulation
30 model could be too time-consuming for climate simulations and numerical weather forecasts,
31 a fast calculation procedure has been developed and made available (for details see Bröde et
32 al. 2008; 2009a; Bröde et al. 2011 elsewhere in this issue).

1 **Conclusion**

2

3 The main objective of this collaboration between 45 scientists from 23 countries was to
4 develop a readily accessible thermal index based on a state-of-the-art thermo-physiological
5 model. The UTCI resulting from this research is intended to significantly enhance
6 applications related to human health and well-being in the fields of public weather services,
7 public health systems, precautionary planning, and climate impact research. The development
8 of UTCI required cooperation of experts from diverse disciplines including thermo-
9 physiology, occupational medicine, physics, meteorology, biometeorological and
10 environmental sciences. After many decades of frustrating attempts by individual researchers
11 working on thermal indices in isolation from cognate disciplines, the UTCI team's
12 multidisciplinary approach facilitated the research synergies necessary for a universal solution
13 to the problem of characterising the human thermal environment. Embedding the UTCI
14 project within a Commission of the International Society of Biometeorology and also a
15 European COST Action provides an international framework for this new climatic index to
16 evolve into a methodological standard.

17

18 The Universal Thermal Climate Index UTCI assesses the outdoor thermal environment for
19 biometeorological applications by simulating the dynamic physiological response with a
20 model of human thermoregulation coupled with a state-of-the-art clothing model. The
21 operational procedure (available as software from the UTCI website <http://www.utci.org>)
22 shows plausible responses to humidity and radiative loads in hot environments, as well as to
23 wind in the cold. UTCI was in good agreement with the assessment of other standards
24 concerned with the thermal environment (Psikuta et al. 2011 elsewhere in this issue). Local
25 cooling of exposed skin, including frostbite risk (wind chill effects), should best be regarded
26 as a transient, rather than a steady-state phenomenon (Shitzer, 2006; Tikuisis and Oszcewski,
27 2002, 2003). The consensus final procedure for cold exposure using UTCI, however, still
28 remains to be determined (Shitzer and Tikuisis, 2011 elsewhere in this issue).

29

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32 Cooperation in Science and Technology, www.cost.eu) supported by the EU RTD Framework

1 Programme, and the International Society of Biometeorology Commission 6, under the
2 umbrella of the World Meteorological Organization's Commission on Climatology CCI.

3

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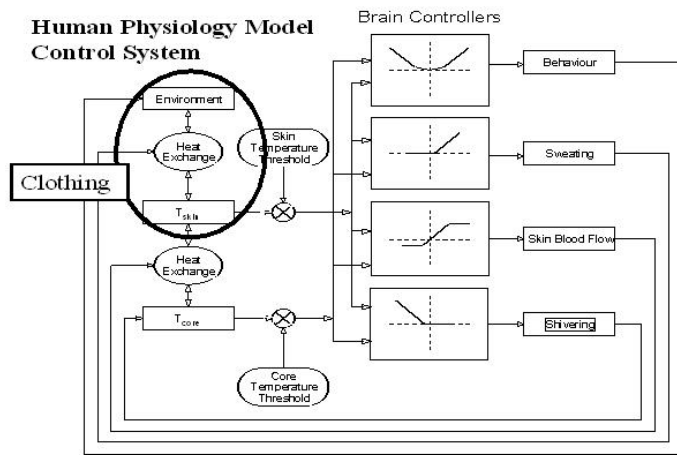
14 **Figures**

15 Figure 1 a, b Schematic representation of human physiological and behavioural
16 thermoregulation (after Havenith 2001, Fiala et al. 2001).

17 Figure 2 The human heat budget (Havenith 2001).

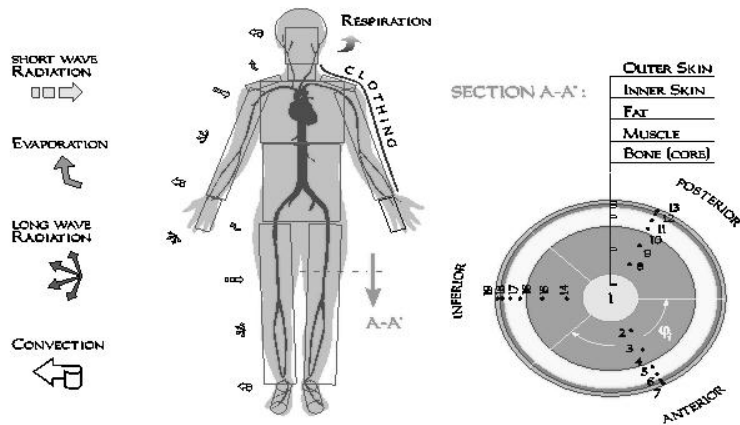
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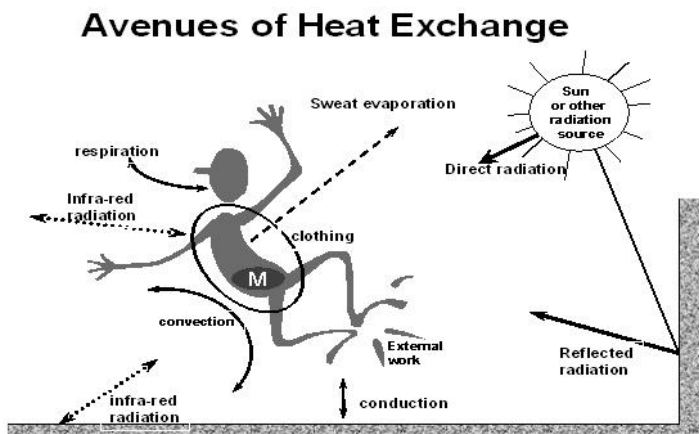
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Figure 1a



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Figure 1b



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Figure 2